EXPERIMENTAL STUDY OF CONTROLLED DISTURBANCES DEVELOPMENT IN A SUPERSONIC BOUNDARY LAYER ON A SWEPT WING

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Introduction

The problem of transition to turbulence in 3-D boundary layers is very important and very complicated. In a 3–D case exist along with the well-known Tollmien – Schlichting waves, which development results to the turbulent transition in the 2-D boundary layers, stationary vortexes with axes directed along the outer streamlines and some traveling waves (not T–S waves). Development of all instability disturbances and their relative role in transition strongly depend on the environmental conditions. Most theoretical and experimental results on stability of a three-dimensional boundary layer are obtained for subsonic flow. Some recent studies in this field are discussed in reviews [1-4] and other papers. However very few theoretical and experimental investigations of supersonic 3-D boundary layer stability have been fulfilled up to date. Malik et al. [5] studied secondary instability on stationary crossflow disturbances in swept cylinder boundary layer at M=3.5. The most unstable traveling crossflow disturbance has a peak frequency of about 50 kHz; and the unstable frequency for secondary instability is an order of magnitude higher than that of the traveling disturbance. Laminar-turbulent transition in a 3-D supersonic boundary layer by mean DNS using the temporal model was studied in [6]. Linear stability analysis shows the dominance of crossflow instability. The secondary instability analysis reveals a broad band of secondary unstable modes traveling in streamwise direction. experimentally and theoretically transition on a swept wing model at M=3.5 was studied in [7]. Using the envelope e^N method for linear stability calculation obtained the N–factor and compared results with the observed transition locations. Traveling disturbances with N=13 provide a good correlation with the transition data. Computed disturbances with frequencies 40-60 kHz have the largest N factors.

The experimental results on the laminar-turbulent transition in three-dimensional boundary layers for M > 1 are described in [7-10]. Stationary structures were registered using different methods of flow visualization. The first experimental studies of instability of a three-dimensional boundary layer at supersonic velocities were conducted in [11-13]. Evolution of natural fluctuations in the boundary layer on a swept wing was studied in [11, 12]. It was shown that the character of distribution of the mean and fluctuating characteristics of the boundary layer is similar to the case of subsonic velocities. A downstream increase in these disturbances was found in analyzing the spectra of natural fluctuations. It was obtained at M=2, that the disturbances growth in three-dimensional boundary layer occurs much faster, than in the flat plate case. The increase of the Mach number up to 3.5 extends frequency band of amplifying disturbances and leads to earlier turbulent transition. The results of an experimental study of evolution of controlled disturbances on a swept-wing model for Mach number M = 2 are presented in [13]. The wave characteristics of traveling waves are obtained.

The objective of present work is an experimental study of nonlinear evolution of controlled disturbances on a swept wing supersonic boundary layer.

Experimental Equipment

The experiments were conducted at the ITAM SB RAS in the M -325 supersonic wind tunnel with test-section dimensions 0.2 × 0.2 ×0.6 m for Mach number M = 2.0 and unit

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Reynolds number $\mathrm{Re}_1 = U/\nu = (6.6\pm0.1)\ 10^6\ \mathrm{m}^{-1}$. A wing model with a 40° sweep angle of the leading edge and a lenticular profile was used in the experiments. The model was mounted at zero incidences in the central section of the test section of the wind tunnel. A sketch of the model and the coordinate system are described in [12, 13]. The model length was 0.26 m, its width was 0.2 m, and the maximum thickness was 20 mm. A generator of localized artificial disturbances was used to introduce controlled oscillations in the boundary layer [14]. The operation principle of the generator is based on a spark discharge in the chamber; its construction is described in [15]. Artificial disturbances were introduced into the boundary layer through an orifice in the working surface of the model, the orifice diameter was 0.42 m, and the frequency of discharge ignition was 20 kHz (which corresponds to disturbances at the fundamental frequency). The source of controlled disturbances was located at a distance $x' = (21.4\pm0.25)$ mm from the leading edge of the model. The origins of the coordinate systems x, y, z and x', y', z' coincided with the position of the source of disturbances.

The oscillations were measured by a constant-temperature hot-wire anemometer. Single-wire tungsten probes of diameter 5 μm and length 0.8 mm was used. The overheat ratio of the wire was 0.8, and the measured disturbances corresponded to mass-flow fluctuations. Artificial disturbances were measured in the layer with $y/\delta = 0.6$ (δ is the boundary-layer thickness). In this layer, the amplitude of disturbances reached the maximum value. The fluctuating and mean characteristics of the flow were measured by an automated data acquisition system [15]. To improve the signal-to-noise ratio, the signal was simultaneously summed over 500 realizations; the length of each realization was 400 μsec. The frequency spectra of disturbances were determined by the discrete Fourier transform

$$e'_{f\beta'}(x',y) = \frac{2}{T}\sum_{j,k} e'\left(x',z'_j,y,t_k\right)\exp\left[-i\left(\beta' z'_j - \omega t_k\right)\right],$$

where $e'(x', z'_j, y, t_k)$ is the digital oscillogram of the fluctuating signal from the hot-wire anemometer averaged over the rea1izations and T is the length of one realization in time. The amplitude and phase of disturbances were found after the discrete Fourier transform from the formulas

$$A_{f\beta'}(x',y) = \{\mathrm{Re}^2[e'_{f\beta'}(x',y)]+\mathrm{Im}^2[e'_{f\beta'}(x',y)]\}^{0,5},$$

$$\Phi_{f\beta'}(x',y) = \mathrm{arctg}\{\mathrm{Im}[e'_{f\beta'}(x',y)]/\mathrm{Re}[e'_{f\beta'}(x',y)]\}.$$

The absolute values of mass-flow fluctuations $(\rho u)'$ were determined by the method proposed by Kosinov et al. [16].

Results and Analysis

The results on evolution of controlled disturbances in the boundary layer on a swept-wing model were obtained in two sets of experiments. The measurements were conducted in x' cross sections by moving the hot-wire probe along the z' coordinate, i.e., parallel to the leading edge of the model, in the layer of maximum fluctuations in the boundary layer for a constant value of the y coordinate. Oscillograms of mass-flow fluctuations along the spanwise coordinate z' were obtained for x' = 20.7, 24.6, 28.4, 32.2 mm (first set) and x' =32.2, 36.1, 39.9 mm (second set). The initial amplitude of disturbances in the second set was higher approximately on 10-20 %. We note that the averaging method used in the experiments allowed us to identify only fluctuations correlated with the source of disturbances.

As for the case of a flat plate, the disturbances are localized in a narrow region [17]. The wave train in the boundary layer on a flat plate was symmetric, whereas the wave train on a swept wing is asymmetric. The oschillograms near $z' = 0$ have a tenon-shaped form, which was also observed in flat-plate experiments with high initial disturbances [17, 18]. Introduction of

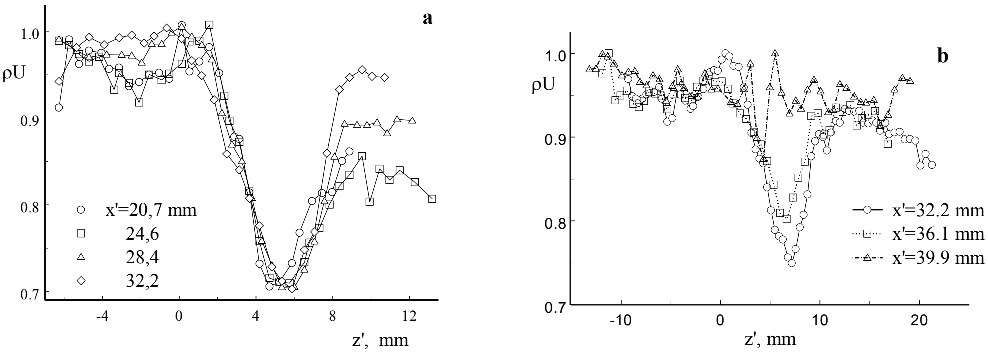
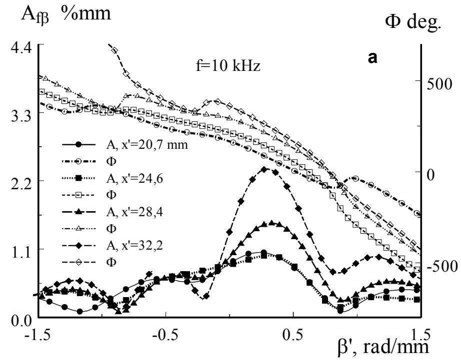


Fig. 1. The distributions of the mass-flow rate ρU over the spanwise coordinate z'.

artificial disturbances distorted the mean flow in the boundary layer. This indicates a nonlinearregime of generation of the source and a high amplitude of initial disturbances. The distributions of the mass-flow rate ρU over the spanwise coordinate z', which are normalized to the maximum flow-rate value, are plotted in Fig. 1. The dependences $\rho U(z')$ were obtained in the boundary layer at a constant distance from the swept-wing surface. The minimum of $\rho U(z')$ near $z' \sim$ 4.5-6.0 mm observed in all distributions is caused by a stationary crossflow disturbances. Steady vortices in a three-dimensional boundary layer were observed in experiments [7-10]. In contrast to the results of these papers, the size of a steady perturbation obtained in our experiments is greater than the scale of cross-flow steady vortices. The position of the minimum of $\rho U(z')$ shifts downstream (along x) at an angle of 3.0-3.5^0 to the x axis, which indicates the downstream entrainment of cross-flow vortices in the boundary layer in the region of the present measurements. This result is similar to that obtained by Gaponenko et al. [19] for a three-dimensional boundary layer at low subsonic velocities of the flow. The amplitude of the stationary disturbances is about 30% and remains practically unchanged in the first set of measurements (Fig.1a). The stationary disturbances damp in the second set (Fig.1b). In the last section (x' =39,9 mm), where practically take place laminar - turbulent transition, a destruction of stationary disturbances is observed.

After the Fourier transform of periodic oscillograms in time, we obtained amplitude-phase distributions of the disturbances along z'. The distributions $A_f(z')$ and $\Phi(z')$ obtained for all the above-mentioned coordinates x' for the fundamental energy-carrying frequencies are given in [20]. It was found that the amplitude of oscillations with frequencies 10, 20, and 30 kHz decreases with increasing x' within the range x' = 20-25 mm. Probably, suppression of the Tollmien-Schlichting waves by the favorable pressure gradient occurred. The growth of disturbances was observed downstream. It must be noted, that simultaneously with decreasing of traveling disturbances small increasing of stationary disturbances take place and vice versa. A slight (3-4^0) smearing of the wave train was observed in the course of its evolution. The z' distributions of the amplitude of disturbances for frequencies of 20 and 30 kHz had two maxima (the right maximum near $z' \sim 7$ mm and the left maximum near $z' \sim 0$). The growth rate of disturbances that refer to the right maximum was much greater. By means of a frequency-wave analysis of the array of fluctuation oscillograms relative to z' and x', we determined the wave characteristics of disturbances with f = 10, 20, arid 30 kHz. Figure 2 shows the amplitude-phase β' spectra of disturbances for f = 10 (a) and 20 kHz (b) for firs set of measurements. The amplitude and phase distributions of disturbances along z', and the amplitude-phase spectra along β' are reminiscent of similar distributions obtained for a subsonic flow at a significant distance



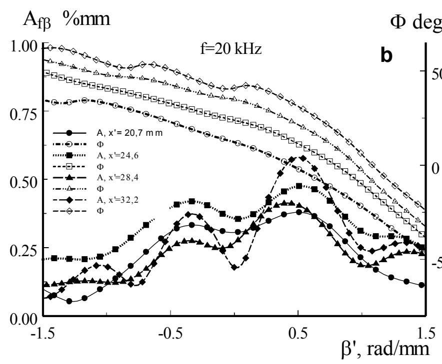


Fig. 2. Amplitude-phase β' spectra of disturbances for f = 10 (a) and 20 kHz (b) for firs set of measurements.

from the source [19]. Predominant growth of the phase along the wing span in the vicinity of the right maximum of the amplitude is typical of traveling waves in a three-dimensional boundary layer. From the amplitude spectra in Fig. 2, it follows that the greatest increase is observed for disturbances with a 10-kHz frequency for β' = 0.2-0.7 rad/mm. On the basis of the phase spectra of disturbances, we can conclude that there exists a range of wavenumbers where the streamwise phase growth is almost linear for β' = const, which allows us to determine the streamwise wavenumber. For each fixed value of β', we determined first the stream-wise wavenumber α_r and then α'_r along the x' axis: $\alpha'_r = (\alpha_r/\cos 40^0 - \beta' \tan 40^0)$. The inclination angle of the wave vector χ' in the plane (x', z') was found from the formula $\chi' = \arctan(\beta'/\alpha'_r)$. The resultant dependences α'_r (β') and χ' (β') are plotted in Fig. 3. It follows from these results that the disturbances with the highest amplitude for f = 10 kHz, like for f = 20 kHz, have an angle of inclination of the wave vector in the plane (x', z') between 60 and 120^0. The disturbances with frequency of 30 kHz did not increase in this flow region. The angle of the group-velocity vector obtained for the most unstable disturbances was about 43^0 in the plane (x', z'), which coincides with the direction of downstream entrainment of the steady disturbances with account of revolution of the coordinate system.

Another character of disturbances evolution is observed in nonlinear stage (second set of measurements). Figure 4 shows the amplitude-phase β' spectra of disturbances for f = 10 (a) and 20 kHz (b) for second set of measurements. The amplitude and phase distributions at the basic frequency remain about same, as well as at earlier stage of evolution. The main differences are observed at subharmonic frequency. The primarily three-dimensional disturbances at the subharmonic frequency are transformed in "two-dimensional". The amplitude of disturbances at subharmonic frequency surpasses amplitude of disturbances at base frequency. In the last section at x' =36.1 mm happen fast destruction of traveling disturbances and stationary structure. The strong growth of

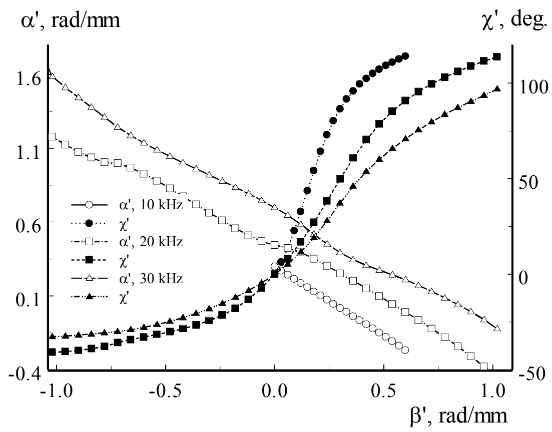


Fig. 3. Dependences α'_r (β') and χ' (β').

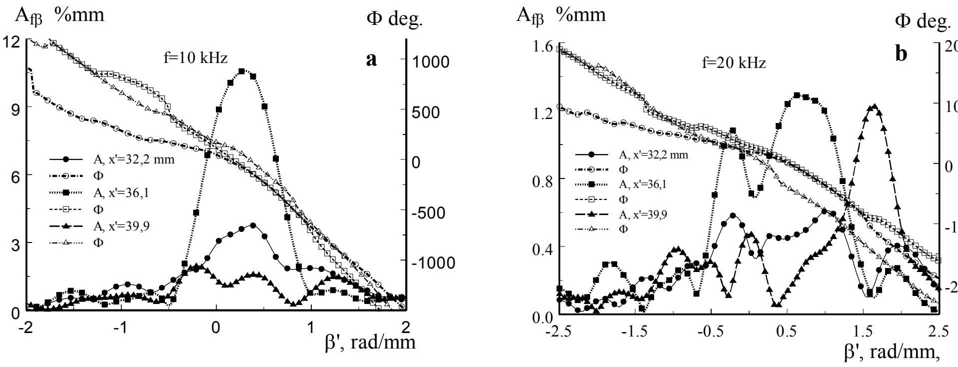


Fig. 4. Amplitude-phase β' spectra of disturbances for *f* = 10 (a) and 20 kHz (b) for second set of measurements.

subharmonic disturbances, on all visibility, is connected to interaction with stationary disturbances. This data allow to assume, that there are the same processes, observed at studying of nonlinear development of controlled disturbances in supersonic boundary layer on the flat plate at large initial amplitudes [17, 18]. The obtained experimental data are in quality correspondence with theoretical results [6]. Mielke & Kleiser wrote "… Then secondary instability modes start growing until strongly nonlinear interaction set in. The final breakdown to turbulence is characterized first by the breakdown of the crossflow vortex and finally the decay of the secondary vortical structures into new smaller structures."

High-frequency oscillations of controlled disturbances were excited simultaneous1y in a wide range of frequencies. The most intensely excited oscillations correspond to 100, 120, and 150 kHz. The high-frequency oscillations were practica1ly equal to zero in initial x' cross sections but increased with increasing x' coordinate. The appearance of high-frequency oscillations is also confirmed by the experiments of Levchenko et al. [11] who studied instability of a three-dimensional supersonic boundary layer on a swept-wing model under natural conditions. A high-frequency wave train was observed in the region f = 140-165 kHz in the spectra of natural oscillations. The excitation of a high-frequency wave train under controlled and natural conditions seems to be related to the cross-flow instability.

Conclusions

Evolution of wave train in swept wing boundary layer was studied in controlled conditions.

The amplitude of a steady cross-flow disturbance was about 30% in first set of measurements. The direction of entrainment of this disturbance made an angle of about 3^0 with the external stream direction. The evolution of disturbances at frequencies of 10, 20, and 30 kHz is similar to the development of traveling waves for subsonic velocities. The angle of inclination of the wave vector for energy-carrying disturbances is directed across the flow, and the group-velocity vector is aligned with the steady cross-flow disturbance. Experimentally obtained, that mechanism of secondary cross-flow instability play main role in laminar-turbulent transition in 3-D supersonic boundary layer.

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